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Climac neutron monitor response to incident iron ions: An application to the 29 Sept 1989 ground level event

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Abstract. We present the response function of the Climax Neutron Monitor to iron ions incident on the upper atmosphere. We have calculated the relative yield function of iron versus protons using the CORSIKA air shower Monte Carlo code. We then multiply the yield function for protons and iron by appropriate incident source spectra to determine the relative neutron monitor response functions. The source spectra we use are those determined for the 29 September 1989 ground level event (GLE), using data from IMP-8, GOES-6/7 and the neutron monitor network which observed this GLE. Like all the GLEs observed with the Climax neutron monitor, the 29 September 1989 event was iron-rich at high energy and had a hard solar energetic (SEP) iron spectrum which extended beyond 500 MeV/nucleon. This event had perhaps the hardest iron spectrum and greatest iron flux at high energy than any other GLE observed at Climax. Despite the fact that, during the peak of this event, the iron flux at GeV/nucleon energies may exceed that of protons, we determine that the integrated neutron monitor response to iron is less than 0.1 of that to protons. Thus it is unlikely that the response of the neutron monitors to iron-rich GLEs is due to the greatly enhanced flux of high energy iron. We discuss this result in terms of the reported correlation between ground level events observed at Climax and iron-rich gradual SEP events simultaneously observed at IMP-8.

1 Introduction

The motivation for this study comes from a remarkable correlation that we have found between the Climax neutron monitor rates and associated solar particle events (SPEs). Whenever we observe a ground level event (GLE) with the Climax neutron monitor the associated SPE is Fe-rich, as measured with the University of Chicago charged particle telescope on the Earth-orbiting satellite IMP-8. Since GLEs are associated with shocks driven by coronal mass ejections (CMEs) the SPEs associated with GLEs are

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Table 1. Ground Level Events Observed at Climax and the Maximum of the Fe/O Ratio for the Associated SPE
(the nominal Fe/O ratio for gradual SPEs is ~0.078)

Date of GLE	Fe/O	Date of GLE	Fe/O
29 Apr 1973	~3.00	19 Oct 1989	0.71
20 Apr 1976	0.49	22 Oct 1989	0.27
19 Sep 1977	1.58	24 Oct 1989	0.88
24 Sep 1977	0.96	15 Nov 1989	0.72
22 Nov 1977	0.77	21 May 1990	1.52
7 May1978	1.27	24 May 1990	1.55
23 Sep 1978	0.58	26 May 1990	1.82
12 Oct 1981	0.80	15 Jun 1991	0.03
26 Nov 1982	0.68	6 Nov 1997	1.01
7 Dec 1982	0.79	2 May 1998	0.75
16 Feb 1984	0.85	14 Jul 2000	0.20
25 Jul 1989	~4.50	15 Apr 2001	0.78
16 Aug 1989	0.58	18 Apr 2001	0.82
29 Sep 1989	0.61		

always gradual events, which normally have Fe/O abundance ratios (at 50-500 MeV/nucleon) about 0.078 (see Dietrich and Lopate, 2001). While it is not rare for gradual SPEs to have high Fe/O abundance ratios, it is somewhat unusual. Table 1 contains a complete list of the GLEs observed with the Climax neutron monitor since the launch of the IMP-8 satellite in 1973. As can be seen, of the 27 GLEs observed with the Climax neutron monitor 26 of the associated SPEs are Fe rich at high energy (50-500 MeV/nucleon). The single GLE which does not have this correlation was the 15 June 1991 GLE, for which the associated flare was central meridian. The poor magnetic connection to Earth associated with central meridian events may account for the difference between this SEP and all the others associated with GLEs observed at Climax.

The SPEs associated with these GLEs all have very hard Fe spectra at high energy (Dietrich and Lopate, 2001). In the case of the 29 September 1989 SPE, the solar energetic Fe spectrum extended beyond 1 GeV/nucleon. The Fe spectra are often significantly harder than the proton spectra, especially at high energy. Thus one possible explanation for the association of GLEs with Fe-rich SPEs

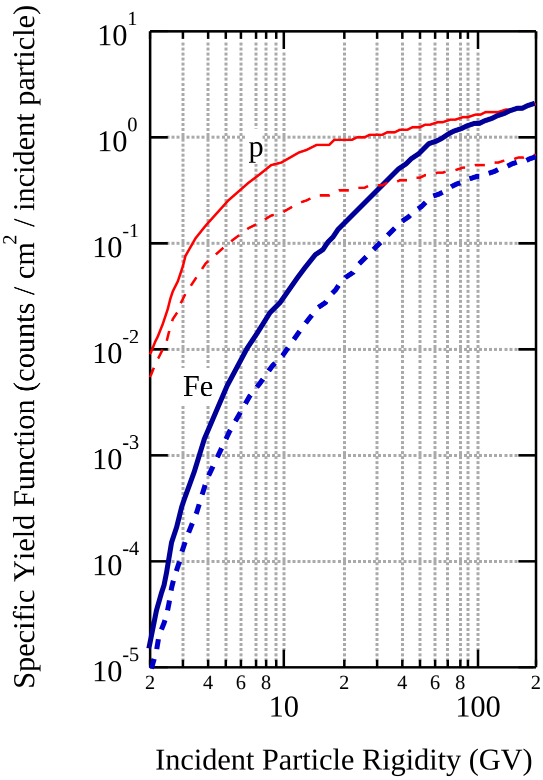

Figure 1 Specific Yield Functions for the Climax neutron monitor to incident primary protons (thin red) and Fe (thick blue) at 0 degrees (solid) and 45 degrees (dashed) incidence.

would be that the solar energetic Fe is creating a signal measurable by ground level neutron monitors. We are addressing this possibility with the analysis presented here.

The Climax neutron monitor is a standard IGY neutron monitor with BF_3 tubes. It is located on a mountaintop at 3400m, which corresponds to ~750g cm^2 of atmosphere above the station. It is in central Colorado, USA at 39.37°N 253.82 °E and has a cutoff rigidity of 3.03 GV for incident primary particles.

2 Monte Carlo Analysis

The first part of our analysis was to acquire a response function of the Climax neutron monitor to secondary air showers particles incident on the neutron monitor tubes themselves. For the Climax neutron monitor response, we use the report of Clem and Dorman (2000). They did a detailed analysis of both IGY and SM-64 response to galactic cosmic rays, using the FLUKA Monte Carlo routines. Figures 5 and 6 from the Clem and Dorman (2000) paper show the response of an NM-64 neutron monitor to several secondary air shower particles as a function of rigidity. They show that a neutron monitor responds best to secondary neutron, protons and pions with a very poor response to muons at low energies; other secondary air shower particles have insignificant response in the neutron monitor. We assumed that the response functions of an IGY neutron monitor to these secondaries would scale proportionally, with the same constant of proportionality for all the secondaries.

The second part of our analysis was to determine the air shower secondaries from both incident protons and incident Fe. In order to complete this analysis we used the CORSIKA air shower Monte Carlo code. This code is available to download on-line. As mentioned previously, the Climax neutron monitor has approximately 750 g cm^2 of atmosphere above it, thus it was at that depth which we stopped the Monte Carlo runs.

We input incident proton and Fe primaries at different rigidities from 2 GV to 200 GV, as this contained the energy region of interest. We also looked at primaries with different angles of incidence, from 0 degrees (vertical) to 60 degrees. We then summed the responses from each of the six secondary species of interest for each primary particle energy and angle of incidence,. into specific yield functions. In Figure 1 we present the specific yield functions for the Climax neutron monitor protons (thin red) and Fe (thick blue) at 0 degrees vertical incidence (solid lines) and at 45 degrees incidence (dashed lines).

As can be seen from Figure 1, at low energy the neutron monitor response to primary protons is significantly greater than the response to primary Fe ions. The main reason for this effect is that low energy Fe ions have significantly greater ionization energy loss in the atmosphere than low energy protons; by ~60 GV the neutron monitor response to protons and Fe is nearly identical.

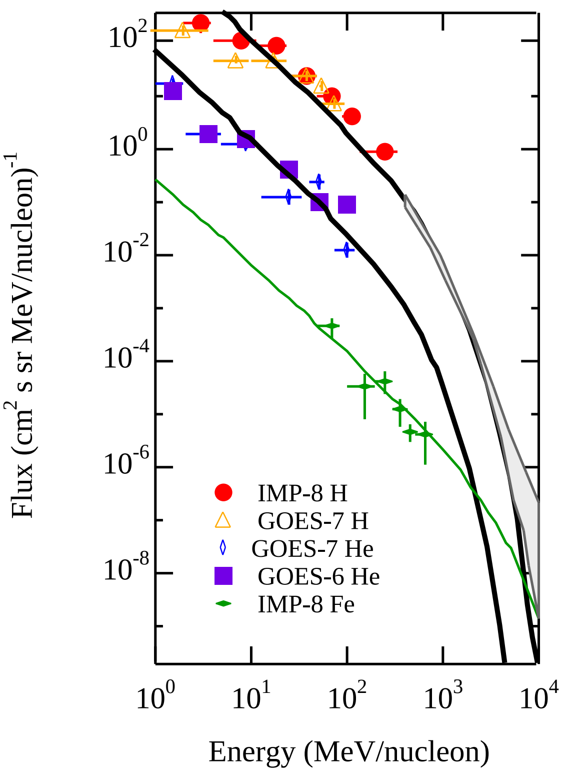

Figure 2. H, He and Fe spectra for the 29 September 1989 SPE. Solid lines are fits of the form derived in Ellison and Ramaty (1985). H and He spectra from Lovell et al. (1998). The dashed gray area is the predicted proton flux from neutron monitors (Lovell et al. 1998) assuming the neutron monitor response is due only to protons. The Fe fit chosen to break at ~3 GeV/nucleon.

3 Application to the 29 September 1989 SPE

In order to determine the neutron monitor response to individual events it is necessary to multiply the specific yield function by the flux intensity for the event under investigation. In our case we have chosen the 29 September 1989 SPE. This event was chosen because the Fe spectrum is known to be significantly harder than the proton spectrum at high energy (Figure 2). Also, during this SPE the University of Chicago instrument on IMP-8 registered solar energetic Fe ions in excess of 500 MeV/nucleon, with an extrapolation indicating that only at about 2-3 GeV/nucleon would the SPE Fe decrease to below galactic cosmic ray levels. Thus the 29 September 1989 SPE would be a good candidate for an SPE which would have energetic Fe registering a response in the Climax neutron monitor.

The proton and helium data were studied before, (Lovell et al., 1998), and we used their reported spectra (reproduced in Figure 2). Figure 2 also includes the IMP-8 measurements of solar energetic Fe for the 29 September 1989 SPE (green diamonds) which is reported here for the first time. We have fit the spacecraft SPE Fe data using the functional form from Ellison and Ramaty, exactly as Lovell et al. did for the H and He data. We chose parameters for the fit form of the Fe spectrum so that the accelerated spectrum broke at ~2 GeV/nucleon, and fell below the galactic cosmic ray Fe background at ~3 GeV/nucleon.

By multiplying the proton and Fe spectra (in Figure 2) by the appropriate proton and Fe specific yield functions (in Figure 1) we derive the differential response function of the Climax neutron monitor to the solar energetic particles of the 29 September 1989 SPE. Figure 3 shows the Climax neutron monitor differential response function for protons (thin red) and Fe (thick blue) solar energetic particles at vertical (solid) and 45 degree (dashed) incidence. As can be seen in Figure 3, while the protons response dominates the Fe response at low rigidities, by ~50 GV the Fe response begins to dominate. This is because the Fe spectrum is significantly harder than the proton spectrum and the Fe flux dominates the proton flux at about 20 GV.

Our final step was to determine over what rigidity range the solar energetic particles which could be observed at Climax would give a response above the galactic cosmic rays. The lower energy is fixed by the geomagnetic cutoff at Climax, which is 3 GV. The upper rigidity was chosen as 3 GeV/nucleon Fe, which is the point at which the calculated solar energetic Fe flux became nearly equal to the galactic cosmic ray Fe flux.

When we converted these energies to rigidities we assumed that the solar energetic Fe had an ionic charge state of +12. This relatively low charge state is consistent with observations of charge states for Fe in gradual SPEs (Reames, 1999). The +12 charge state also had the effect of increasing the maximum rigidity observable during this event, which emphasized the Fe contribution to the Climax neutron monitor rate. The resulting range of rigidities for primary protons and Fe ran from 3-18 GV.

In order to determine the relative response of protons and Fe we integrated the response functions over the rigidity range 3-18 GV (black arrow) and summed the responses for the possible angles of incidence, assuming that the primaries were entering the atmosphere above Climax isotropically. The ratio for the relative response of the Climax neutron monitor to solar energetic particles during the 29 September 1989 SPE is Fe/p = 0.0936.

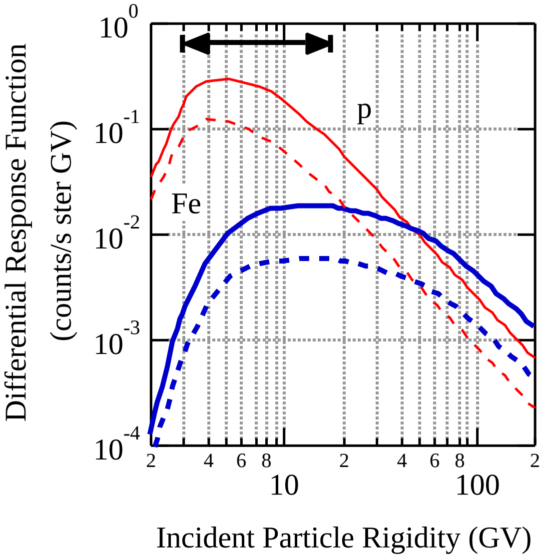

Figure 3. The proton (thin red) and Fe (thick blue) differential response functions at 0 degrees (solid) and 45 degrees (dashed) incidence for the Climax neutron monitor during the 29 September 1989 SPE. The black arrow indicates the range of rigidities of SPE ions which would give response at Climax.

4 Conclusions

Our analysis of the Climax neutron monitor response to incident solar energetic protons and Fe during the 29 September 1989 SPE indicated that the integrated Fe response was only 9.36% of the proton response. This value was an upper limit since we assumed that Fe had an ionic charge state of +12 and that the solar energetic Fe flux was above background through 3 GeV/nucleon. If the ionic charge state of Fe were greater than +12 or the Fe flux fell below the galactic cosmic ray Fe flux below 3 GeV/nucleon the Fe/p response would decrease.

Our conclusion is that even in large SPEs with very hard Fe spectra, the solar energetic Fe would have at most a small effect on the Climax neutron monitor response during associated GLEs. Thus the correlation between Fe-rich SPEs and GLEs observed at Climax must be due to an acceleration phenomenon associated with solar energetic protons.

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